The Next Contender in High Speed Transport Elon Musks Hyperloop

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Elon Musk, progressive futurist and business magnate has proposed a fifth mode of transportation called the Hyperloop. Just as he did with the resurrection of electric vehicle, and the privatization of space flight, Musk is taking the established concepts of the vactrain and maglev technology and is attempting to bring it back into the spotlight but with key improvements. This paper attempts to provide a brief historical literature review of High Speed Transport to Very High Speed Transit (VHST) and to discuss the limitations of the existing and theoretical technologies of Maglev trains and evacuated tube transport. The Hyperloop is proposed as the next contender in High Speed Transport, and a simplified energy analysis is performed to aid in evaluating the feasibility of the Hyperloop. This paper also attempts to highlight several features of the Hyperloop that distinguishes it from traditional vactrains and evacuated tube technologies by using capsules or pods to travel in a medium-pressure environment as opposed to a difficult-to-maintain vacuum environment. A diffuser-compressor-nozzle system has also been proposed to overcome the Kantrowitz Limit. This paper reviews the Hyperloop concept and its specific advantages to the future development of a cost-effective and sustainable high-speed mass transport technology.

Introduction

Oil fueled cars, trucks, and planes have dominated the twentieth century transport. Due to the global climate change, increasing air quality concerns, and the desire for energy efficiency and sustainability, the global transportation system is in need of new and disruptive transportation technologies. High Speed Rail (HSR) as it is commonly referred today involves trains traveling at speeds less than 300 mph[1]. Building trains in this era of technological advancement, Big Data, and the internet, energy efficiency and stainability seems shortsighted. Since public transit is encouraged in order to reduce GHG emissions, reliance on foreign oil, and to reduce traffic congestion, implementation of newer more efficient technologies also needs to be more encouraged, specifically transportation models that run off of renewable energies. The traditional train is neither an energy efficient mode of transport nor is it run off renewable sources. The traditional train is the grandfather of modern mass transportation. Oak Ridge National Laboratory Transportation Energy Data Book compiled a breakdown of the energy efficiency of the familiar modes of transportation and their corresponding energy efficiency in terms of Barrels of Oil or Oil Equivalent Per 10,000 Passenger Miles.

As can be seen from Figure 1, the oil based 20th century modes of transport use around five to eight barrels of oil equivalent per Passenger Mile (per passenger, per mile). The intercity bus had about 1.5 barrels of oil equivalent due to the fact it can transport many people long distances (i.e. carpooling effect). The only remaining bar in Figure 1 is the new and growing technology of Magnetically Levitated Trains[2].

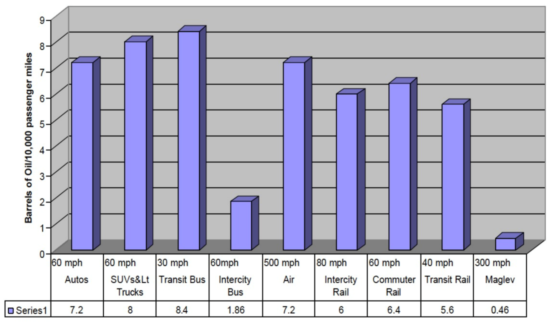

FIG. 1: Energy Consumption of Various Modes of Transport

Maglev Trains

The current growing mass transport technology is the Magnetically Levitating "Maglev"trains. Maglev trains have already been built in Japan, China, and Germany showing new faster more efficient technology is already being utilized[1]. Maglev trains are magnetically levitated vehicles that travel above conductive guide ways[1]. They are therefore currently more efficient due to there being no mechanical contact of Maglev vehicles and their guide ways, so that friction and wear do not limit the Maglev speeds. The limiting factor for Maglev speeds is primarily air resistance. The practical limit for Maglev vehicles is about 300 mph since air resistance is proportional to the cube of the vehicles speed. Trying to go faster than 300 mph becomes really energy intensive and uneconomical[1]. Additionally, Maglev trains have large capital costs and have struggled to be introduced into the U.S. transportation market[1].

Evacuated Tube Technology

Evacuated tube technology is the theoretical next step in High Speed Transport technologies. The concept was put forward in the 1970s by Robert M. Salter of RAND Corporation and coined the term Very High Speed Transit (VHST). After the invention of Maglev technology eliminating frictional losses in high-speed transport, ,the next step is to overcome the dominating drag caused by air resistance that limits speeds to 300 mph. R.M. Salter was on a search of a pollution-free transport method that could operate at speeds competitive with aircraft[3]. Salter suggested electromagnetically levitated and propelled cars in an evacuated tunnel. The concept is evacuating tubes to a complete vacuum, such that is found in space, and car sized passenger capsules would travel through the tubes on Maglev technology up to speeds of 14,000 mph[3]. A company based out of Longmont, CO, by the name of Evacuated Tube Transport Technologies (ET3) of ET3 Global Alliance Inc. has plans to build a production ready demonstration of ET3 to operate at 375 mph. Their slogan is Space Travel on Earth[4].

Traveling through a perfect vacuum with zero air resistance and zero friction is the ideal situation in terms of energy efficiency; however, creating the needed environment for this ideal case is extremely energy intensive due to the large number of vacuum pumps needed. Figure 2 comes from Maglev 2,000 website showing Energy Consumption vs. Transport Mode in Barrels of Oil Equivalent per 10,000 Passenger Miles excluding the costs of creating and maintaining the vacuum tubes.

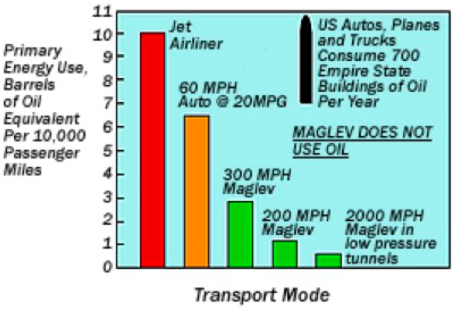

FIG. 2

It is clear that the next big breakthrough with high-speed transport will have to address the obstacle of air resistance. Although creating Space on Earth or a perfect vacuum is possible, it is an extremely energy intensive process that needs some of the most powerful vacuum pumps and new materials to limit outgassing and potential air leaks. Additionally, going up to 14,000 mph has a host of other challenges. Propulsion and g-forces required to get to those speeds will not only make it uncomfortable, but practically impossible and virtually science fiction. Society has Maglev trains currently in operation but they are struggling to get fully adopted due to the high cost at a maximum speed of 300 mph. On the other hand, evacuated tube technology is so ambitious and futuristic that it teeters on the line of science vs. science fiction. Why not something in the middle of these technologies?

Elon Musk's Hyperloop

Elon Musk, CEO of Tesla Motors and SpaceX has proposed a fifth mode of transportation called the Hyperloop. Just as he did with the resurrection of electric vehicle, and the privatization of space flight, Musk has taken established concepts of the evacuated tube technology and maglev technology and is attempting to bring it back into the spotlight but with key improvements. California approved a bill to build a HSR along the coast connecting Los Angeles to San Francisco. The HSR has a proposed cost of $68.4 billion USD. Elon Musks proposed Hyperloop claims to be faster, safer, and cheaper at an estimated cost of $7.5 billion.[5] It is difficult to estimate if $7.5 billion is a valid estimate in such early conceptual stages since the Hyperloop has never been built or even designed. Regardless, this paper attempts to provide examples of several key components of the Hyperloop concept that provide a cost advantage over the traditional high speed transportation technologies such as Maglev trains and Evacuated Tube Technology (ET3).

The Hyperloop is a steel construction medium vacuum pressure tube that accelerates pods or capsules through the tube at up to 760 mph on proposed air bearings and/or proven maglev technology. It is meant to be propelled by solar powered linear induction motors and considering it is in a low-pressure environment needs substantially less power to travel. According to Musks white paper Hyperloop Alpha, the Hyperloop makes economic sense if passengers are traveling within 500-mile distances. This is an important characteristic in that the Hyperloop is meant for direct travel between two places such as city pairs. It is not meant to stop along the way with multiple destinations instead the focus is on travel between two major urban areas. Specifically coupled cities such as San FranciscoL.A., Chicago-St. Louis, Chicago-Milwaukee, Chicago-Indianapolis, New York City-Boston, New York City-Philadelphia, Philadelphia-Baltimore, Houston-New Orleans, Orland-Miami, Paris-Lyon, Paris-Brussels, as well as others.

Medium Pressure vs Ultra High Vaccum Pressure Energy Analysis

The Hyperloop differs from the previously mentioned technologies in that they are conceptually and theoretically possible, but are not practical. Not being able to go faster than 300 mph limits how fast a passenger arrives at their destination and prohibits capital intensive construction projects when the gains (i.e. time of arrival)

are small relative to the investment (i.e. cost of building a Maglev train). As for ET3 technology, achieving and maintaining an Ultra High Vacuum (UHV) such as the vacuum of space for a length of a 500-mile tube is very difficult and immensely energy intensive, albeit the zero air resistance which is so appealing.

In order to provide estimates of energy use data of the Hyperloop, the level of energy use will depend on technical design characteristics of the Hyperloop such as size, shape, and number passengers per pod and operational characteristics such as acceleration and deceleration intensity, maximum speed, and distance between stations. However, due to the fact there is limited literature on the Hyperloop, several arbitrary parameters will be assumed from Hyperloop Alpha, and this paper will only focus on the energy consumption of the pumping down the tube and attempt to quantify the energy saved in power required to overcome air resistance at 760 mph. Further work will attempt to do a full Lifecycle Energy Analysis.

In order to realize the energy savings, it is important to understand that the power required to overcome air resistance is proportional to the cube of the vehicles speed.

$$P = F_d \times v = \frac{1}{2}\rho v^3 A C_d, \qquad (1)$$

P is the power, F_d is the drag force, v is the velocity of the vehicle, ρ is the air density, A the area of the vehicle and C_d is the drag coefficient.

The Hyperloop Passenger tube design pressure has been selected to be 0.75 torr (0.014 PSI) according to Hyperloop Alpha, which is typically considered a medium vacuum. The reason for this medium vacuum pressure of 0.75 torr is because the "efficiency of industrial vacuum pumps decreases exponentially as the pressure is reduced and at this pressure there is minimal air resistance to any traveling vehicles." Additionally, Assuming a vehicle with a $20ft^2$ cross sectional area and a common drag coefficient of 0.3 and at vehicle speeds of 760 mph, the power was calculated using Equation 1 at tube pressures ranging from 0.0145 PSI all the way up to 14.7 PSI atmospheric pressure. Table 1 and Figure 3 shows the linear relationship of power with respect to tube pressure:

TABLE I: Horsepower Required to overcome Air Resistance in Hyperloop Tube

Velocity [mph]	0.01 PSI [hp]	14.7 PSI [hp]
50	0.01	5.41
80	0.02	22.16
100	0.04	43.28
200	0.34	346.25
300	1.15	1168.60
400	2.73	2770.01
500	5.34	5410.17
760	18.75	18999.48

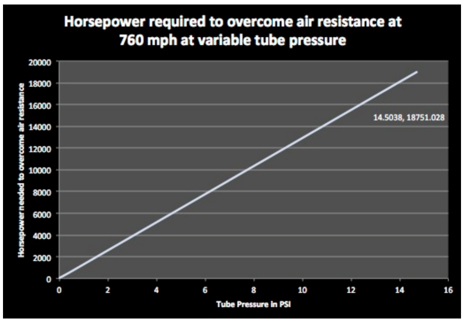

FIG. 3

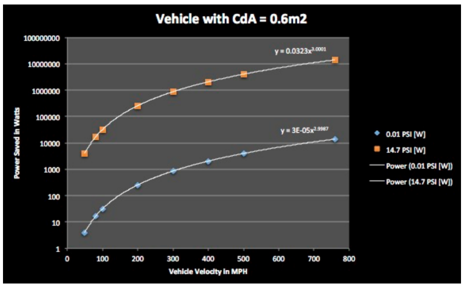

FIG. 4

Ignoring minor other losses such as friction, eddy currents, and elevation changes, and only focusing on air resistance, it is interesting to note that the horsepower required for a vehicle to overcome atmospheric 14.7 PSI air resistance for 200 mph, a vehicle would need at least 346.25 hp which is comparable to V8 muscle cars. For the same vehicle to travel up to 760 mph would require 19,000 hp which is about the horsepower of 50 muscle cars.

It is also evident the air resistance the driver feels at 50 mph (5.41 hp) is about the same resistance the same driver would feel at 500 mph inside the Hyperloop tube. The resistance felt whenthe Hyperloop pod traveling at its maximum theoretical speed would feel like a car traveling at near 80 mph on the expressway. It is also apparent that even at medium vacuum pressures of 0.75 torr (0.0145 PSI) there is 3 orders of magnitude less air resistance which translates into 3 orders of magnitude less power required and substantial energy savings for the Hyperloop Pods.

In order to make sense of the energy savings of the pod in reduced air resistance and to calculate the true energy savings it is important to take into account energy used to create the Hyperloop mediumvacuum. Largest energy consumption is assumed to come from the vacuum pumps to pump down the Hyperloop tube to 100 Pa (0.75 torr) pressures. The evacuation of time for a vacuum pump can be calculated by:

$$t = \frac{V}{q \ln \frac{P_o}{P_f}}, \qquad (2)$$

where t is the evacuation time, V the volume evacuated, q the volume flow rate capacity of the pump, p_o the intial atmospheric pressure, and p_f the end vacuum pressure.

The Hyperloop Passenger version tube inner diameter is to be 7 ft, 4 in. (2.23 m) and a cross sectional area of 42.2 ft^2 (3.91 m^2). Assuming a 270 mile tube (434,523 m) round trip Los Angeles to Las Vegas proposed route:

$$2 \times 3.91 \text{ m}^2 \times 434,523 \text{ m} = 3.39797 \times 10^6 \text{ m}^3, \qquad (3)$$

V is the air volume in the tube.

Assuming the tube would be pumped down during off peak Pacific Gas and Electric Company utility hours from 9:30 pm to 8:30 am (11 hours) at electricity rate for an E20 Industrial Primary Firm customer at $49.28/day meter charge, $18.15/kW summer demand charge, and $0.0787/kWh energy charge[6]. Rearranging Equation 2 from above and solving for needed volumetric flow rate capacity of a vacuum pump gives:

$$q = \frac{V}{t \ln \frac{P_o}{P_f}} = 12.2473 \ \frac{\text{m}^3}{\text{sec}} \qquad (4)$$

Or for the needed flow:

$$12.2473 \ \frac{\text{m}^3}{\text{s}} \times \ 3,600 \ \frac{\text{s}}{\text{hr}} = 44,090.2 \ \frac{\text{m}^3}{\text{hr}} \qquad (5)$$

A commercial vacuum pump company Vacuum Research Corp located in Pittsburgh, Pennsylvania was chosen to supply up to 72 $\frac{m^3}{hr}$ Vacuum Pumps. Model DS1000C Dry Scoll Pump was selected with a cost of $17,880/unit and a power draw of 1.4 kW (1.88 hp) with the capability to pump down to 7.5E-3 torr. These pumps were arbitrarily chosen due to their commercially available specifications and cost numbers. Note that the actual Hyperloop may use different size, and a different number of pumps that may vary from the analysis hereafter. Furthermore, the pump energy calculation is to provide an intuitive qualitative magnitude of energy use, which in reality will change depending on the actual design of the tube. These selected pumps are two orders of magnitude stronger than is needed for the Hyperloop Passenger tube design pressure of 0.75 torr. The last assumption to be mentioned is the energy calculation assumes running the pumps initially with an airtight system which most likely will not be the case in a real Hyperloop. It is safe to assume the tube will have air leaks in at some rate that will need to be pumped out continuously however, this leak rate has not been taken into account. Future work must take into account air leak rates into the tube for more realistic results.

The number of vacuum pumps (Model DS1000 C)required is found by:

$$\frac{44090.2 \ \frac{\text{m}^3}{\text{hr}}}{72 \ \frac{\text{m}^3}{\text{hr}}} = 613 \qquad (6)$$

The power requirement then would be:

$$1.4 \text{ kW} \times \ 613 \text{ pumps} = 858.2 \text{ kW} \qquad (7)$$

or

$$1.4 \text{ kW} \times 613 \text{ pumps} \times 11 \text{ hours} = 9440.2 \text{ kWh} \qquad (8)$$

Lastly the cost of pumping down the Hyperloop Passenger tube overnight would cost:

$$\$18.15 \ \frac{1}{\text{kW}} \times \ 858.2 \text{ kW} = \$15576.33 \qquad (9)$$

assuming pumping during peak hours.

This would result in an energy Charge of

$$\$0.0787 \ \frac{1}{\text{kWh}} \times 9440.2 \text{ kWh} = \$742.94 \qquad (10)$$

As can be seen from the simplified energy calculation, the energy usage to pump down the tube to 0.75 torr in 11 hours would cost $742.17 during off peak hours for only providing electricity to 613 pump motors. If the Hyperloop tube was pumped down during on-peak hours the Demand Charge would be applied and the cost of the same amount of electricity would cost approximately $16,000. Savings can be realized just depending on the time of day to pump down the Hyperloop tube. Having an emission free grid to power the loop can in theory make it green and much more environmentally friendly.

The Kantrowitz Limit

The Kantrowitz Limit relates to the inlet flow of jet engines and rockets when operating at subsonic and supersonic velocities[5]. This is the upper limit when a fluid, such as air, gets choked and no matter how fast the engine is moving, the air cannot move faster than the speed of sound (at a fixed area, density, and pressure). Traveling in anything but an Ultra High Vacuum will create a pressurization effect like a simple internal combustion engine piston in its cylinder. The buildup of pressure in front of the pod will essentially push it back and slow it down. Jeffrey Chin, et. al. from the NASA Glenn Research Center performed some calculations and modeling in their paper *Open-Source Conceptual Sizing Models for the Hyperloop Passenger Pod* that showed that for a pod traveling at the speed of sound at Mach 1, the area of the pod would have to be zero, i.e. non-existent[7]. Chin, et. al. found that area ratios of 0.6 to be optimal, however, this would only yield pod velocities of Mach 0.3-0.4 (203 307 mph)[7]. However, the proposed solution to the Kantrowitz Limit is to put a large radial fan with compressor to move a portion of the air in the front of the pod to the back. Furthermore, a fraction of the air can be salvaged and used to supply compressed air to the suggested air bearings or magnetic levitation so the pod can glide on a thin air film[5]. This is a possible solution to the Kantrowitz Limit problem and will provide additional thrust for the Hyperloop to potentially reach theoretical speeds of 760 mph.

Conclusion

This paper has reviewed current maglev technology along with the theoretical evacuated tube technology and came to the conclusion that the Hyperloop is feasible and if properly designed, has the potential to be much more efficient in terms of energy usage of pods traversing down the tube. The Hyperloop has the potential to be the next breakthrough in High Speed Transport. If society wants transportation to go faster than 300 mph, it will need to be in reduced pressure atmospheres. The only way to efficiently exceed 300 mph will be aircrafts in high altitude atmospheres, or to create a partially evacuated medium vacuum tube roadway for transporting vehicles resulting in substantially less air drag by 3 orders of magnitude, such as the Hyperloop. Furthermore, pumping down the Hyperloop tube has been shown to be feasible in terms of tube pump down energy usage when operated and pumped down during off peak hours.

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[2] ORNL, Oak Ridge National Laboratory, Transportation Energy Conservation Division (N/A).
[3] R. M. Salter (1972).
[4] ET3 Global Alliance, *Evacuated Tube Transport Technology*, URL `et3.net`.
[5] E. Musk (2013).
[6] PG&E, *Electric Rates* (2015), URL `www.pge.com/tariffs/electric.shtml#INDUSTRIAL`.
[7] J. Chin, AIAA SciTech (2015).